Ferroelectric FET Coupled-Oscillatory Network for Edge Detection

PURDUE UNIVERSITY

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Research Background

CMOS-based Oscillator

A. Mallick, *et al.*, *Nat. Commum*, **11**, 2020.

10 transistors and 2 capacitors

Spin-Torque Oscillator

M. Ku, *et al.*, *Phys. Rev. Appl*, **14**, 2020.

J. Torrejon, *et al.*, *Nature*, **547**, 2017.

Not compatible with Si Process
Large energy consumption

Metal-Insulator Transition based Oscillator

S. Dutta, *et al.*, *Nat. Commum*, **10**, 2019.

Not compatible with Si Process
Temperature sensitive

FeFET-based Oscillator (PZT Capacitor)

Z. Wang, *et al.*, *IEEE J. Explot. Solid-State Computat*, **5**, 2019.

Limitations on Si process
Difficult to scale down

Research Approaches and Overview

$Hf_{0.5}Zr_{0.5}O_2$ (HZO)-based FeFET and FeFET-based oscillator circuit

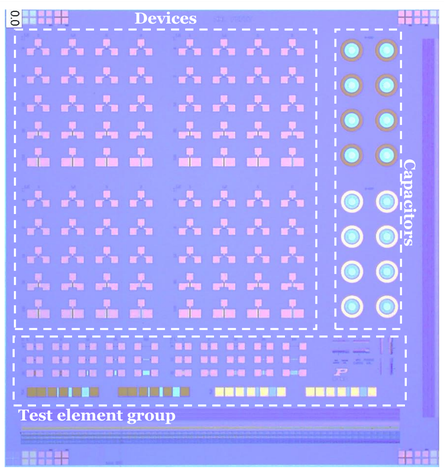
- Smaller number of components (4T 2C for a single oscillator circuit)
- Energy efficiency
- Si process compatibility
- Scalability

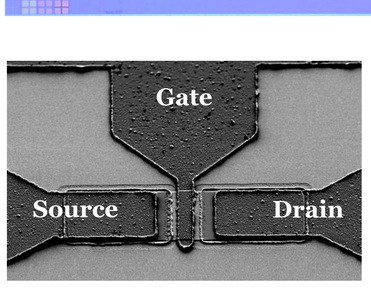
Device Fabrication and Modeling
- FeCap
- *P*-type FeFET
- Device Modeling

SPICE Simulation
- Inverter
- Single-Oscillator Circuit
- Coupled-Oscillator Circuit

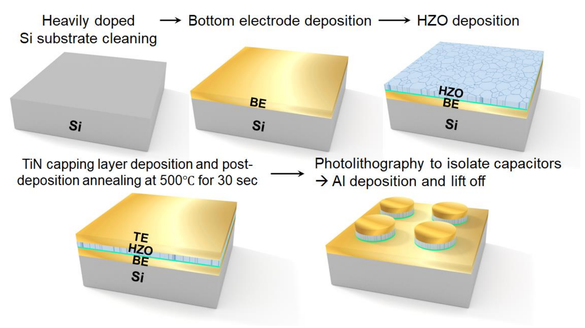
Coupled-Oscillatory Network Simulation
- Theoretical Understanding
- Coupled-Oscillatory Network

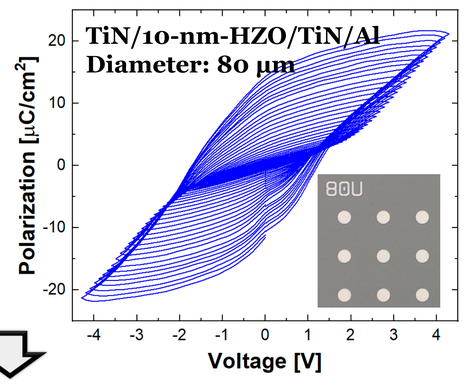
Device Fabrication





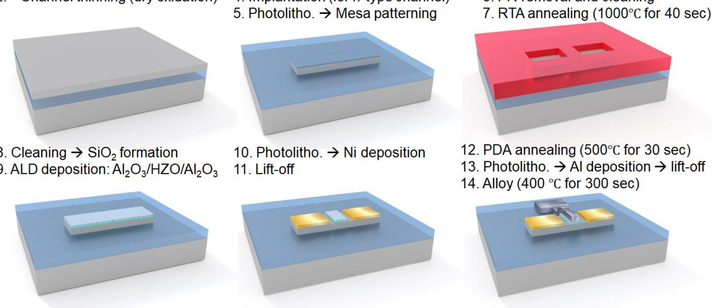
1) Ferroelectric capacitor

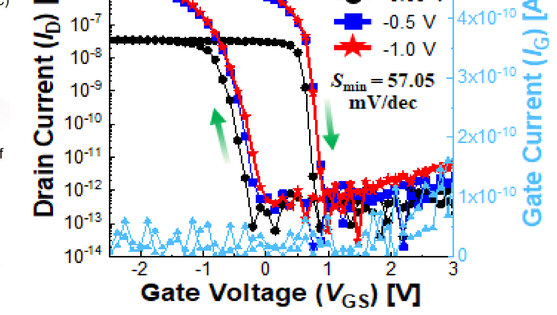




2) Ferroelectric FET

1. SOI wafer cleaning
2. Channel thinning (dry oxidation)
3. Screen oxide growth
4. Implantation (for *n*-type channel)
5. Photolitho. → Mesa patterning
6. PR removal and cleaning
7. RTA annealing (1000℃ for 40 sec)
8. Cleaning → SiO_2 formation
9. ALD deposition: Al_2O_3/HZO/Al_2O_3
10. Photolitho. → Ni deposition
11. Lift-off
12. PDA annealing (500℃ for 30 sec)
13. Photolitho. → Al deposition → lift-off
14. Alloy (400 ℃ for 300 sec)



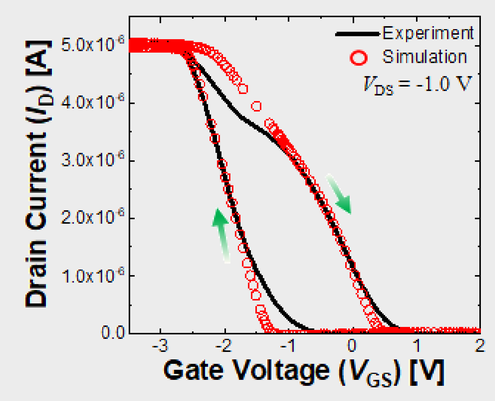


Device Modeling

- **PTM + Preisach model**

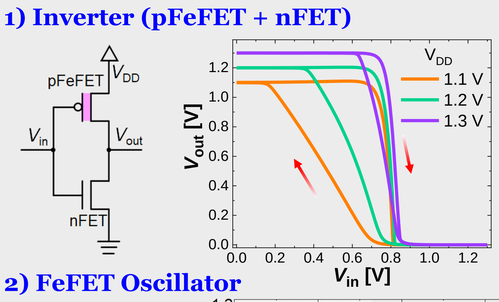
$$P_{sat}(E) = P_s \tanh\left[\left(E - E_c\right)/2\delta\right]$$

$$\delta = E_c\left[\ln\left(\frac{1+P_r/P_s}{1-P_r/P_s}\right)\right]^{-1}$$



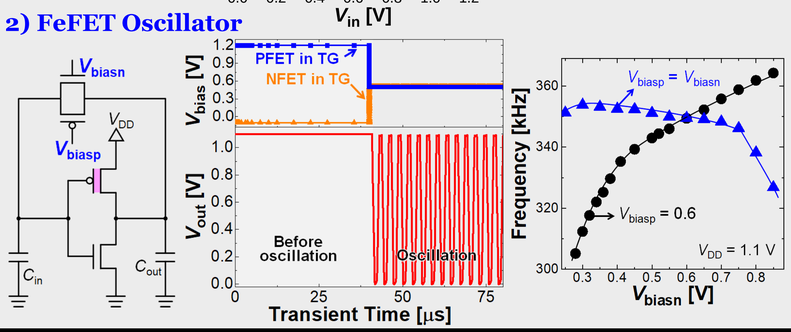
SPICE Simulation

1) Inverter (pFeFET + nFET)



V_{in}	Schmitt Trigger Operation
0	V_{out} is high
0 → V_{DD}	Once V_{in} touches $V_{trip,n}$, nFET turns on and V_{out} goes to low.
V_{DD}	V_{out} is low
V_{DD} → 0	Changed $V_{trip,p}$ due to the forward sweep of V_{in} results Schmitt Trigger operation.

2) FeFET Oscillator



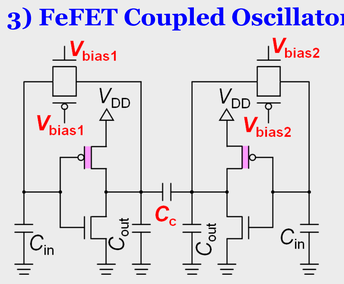
- Oscillation triggering is controlled by transmission gate
- Oscillation frequency can be designed by the equation below:

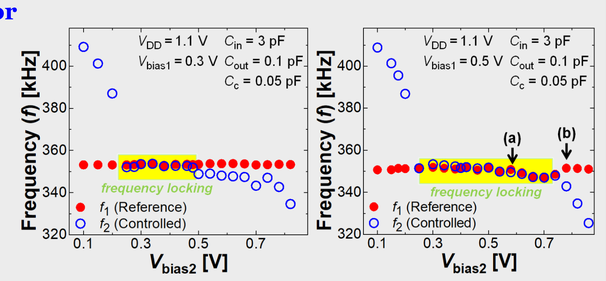
$$f = \left(2\alpha \cdot \left\{R_{on} \cdot C_{out,eff} + C_{in,eff} \cdot \left(R_{on} + R_{TG}\right)\right\} + t_{p,LH} + t_{p,HL}\right)^{-1}$$

the factor α relates (dis)charging delay of C_{in} to the voltage swing at the input node

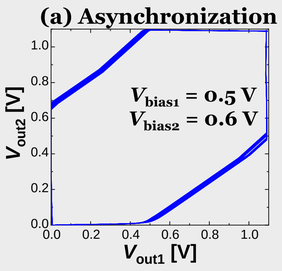
- Energy consumption per a single cycle: 0.84 nJ (V_{DD} = 0.9 V) ~ 3.97 nJ (V_{DD} = 1.2 V). This is at least 29x lower compared to the previous work.

3) FeFET Coupled Oscillator

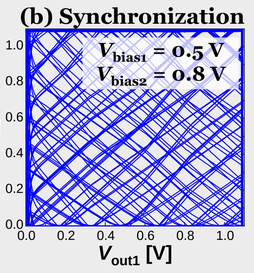


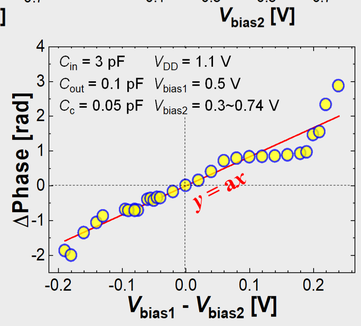


(a) Asynchronization



(b) Synchronization





FeFET Coupled-Oscillatory Network

❖Theoretical Approach

➢ **Derivation of Equations**

$$\psi_i = A_i \cos(\omega t - \delta_i)$$

$\psi = \psi_1 + \psi_2 + \cdots + \psi_n$ ∴ Harmonic addition theorem

$$= \sum_{i=1}^{n} A_i \cos(\omega t - \delta_i) = A\cos(\omega t - \delta)$$

where $A^2 = \sum_{i=1}^{n}\sum_{j=1}^{n} A_i A_j \cos(\delta_i - \delta_j)$

Considering reference signal as n+1th input,

$$A^2 = \sum_{i=1}^{n}\sum_{j=1}^{n} A_i A_j \cos(\delta_i - \delta_j) + 2A_{ref}\sum_{i=1}^{n} A_i \cos(\delta_i) + {A_{ref}}^2$$

Approximate the trigonometric function "cos"

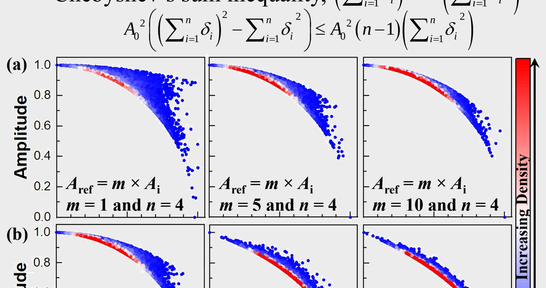
$$A^2 = \boxed{\left(A_0 n + A_{ref}\right)^2} - \boxed{\left((n-1){A_0}^2 + A_{ref}A_0\right)\sum_{i=1}^{n}\delta_i^2} + \boxed{{A_0}^2\left(\left(\sum_{i=1}^{n}\delta_i\right)^2 - \sum_{i=1}^{n}\delta_i^2\right)}$$

Const. (δ indep.) | Proportional to L2² | Error term

➢ **Ways of Reducing Errors**

Chebyshev's sum inequality, $\left(\sum_{i=1}^{n}\delta_i\right)^2 \le n\left(\sum_{i=1}^{n}\delta_i^2\right)$

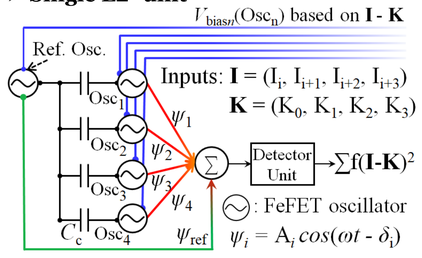
$${A_0}^2\left(\left(\sum_{i=1}^{n}\delta_i\right)^2 - \sum_{i=1}^{n}\delta_i^2\right) \le {A_0}^2(n-1)\left(\sum_{i=1}^{n}\delta_i^2\right)$$



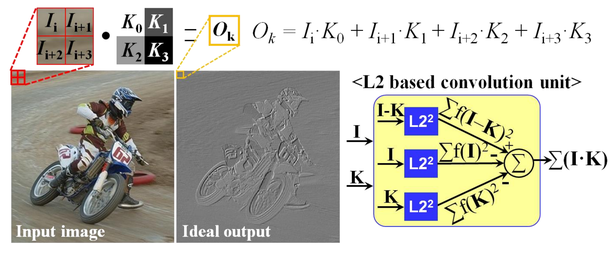
- Increasing the A_{ref} ($A_{ref} = m \cdot A_i$)
- Increasing the number of oscillators (n)

❖Applications

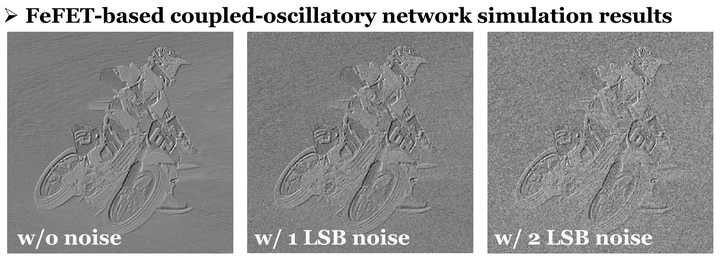
➢ **Single L2² unit**

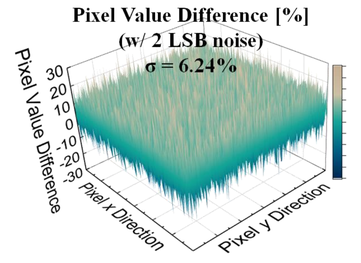


➢ **Convolutional operation approach**



➢ **FeFET-based coupled-oscillatory network simulation results**





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